



Microstructural and Material Quality Effects on Rolling Contact Fatigue of Highly Elastic Intermetallic Ball Bearings

Christopher DellaCorte, S. Adam Howard
Fransua Thomas, and Malcolm K. Stanford
NASA, Glenn Research Center
Cleveland, Ohio

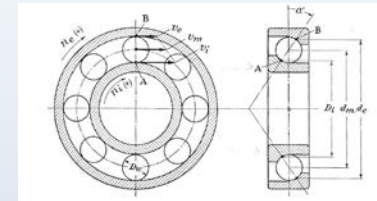
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Bearing Material: State-of-Art (SOA)

(Current suite of candidates is severely limited)

- Four general types of bearing materials:
 - Steels (Corrosion resistant steels, martensitic, austenitic)
 - Ceramics (Si_3N_4 balls + steel races, a.k.a., hybrid bearings)
 - Superalloys (e.g., jet turbine blade alloys)
 - Non-ferrous alloys (bronze, nylon etc.)
- Each of these has inherent shortcomings:
 - Hard steels are prone to rusting (even “stainless steels” like 440C)
 - Superalloys and austenitic stainless steels (304ss) are soft.
 - Ceramics have thermal expansion mismatch and dent steel races
 - Non-Ferrous materials are weak and lack temperature capabilities
- No known bearing material blends all the desired attributes:
 - High hardness, corrosion immunity, toughness, surface finish, electrical conductivity, non-magnetic, manufacturability, etc.

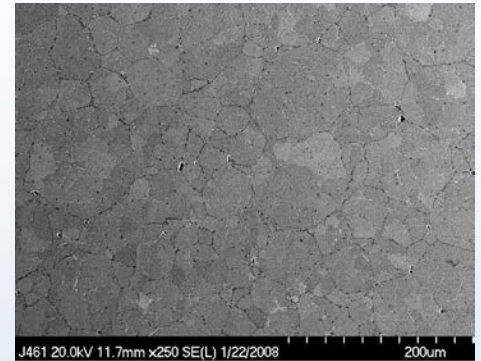




New approach: 60NiTi-Superelastic

(Hard but resilient material based upon shape memory alloys)

- 60NiTi Basics: market name NiTiNOL 60
 - Invented by W.J. Buehler (late 1950's) at the Naval Ordnance Laboratory (NiTiNOL stands for Nickel-Titanium Naval Ordnance Lab).
 - Casting (mix, melt, pour) was original process.
 - Contains 60 wt% Nickel and 40 wt% Titanium
 - 60NiTi is not a metal or a ceramic: a weakly ordered inter-metallic compound.
 - A close cousin to the shape memory alloy, NiTiNOL 55, but 60NiTi is dimensionally stable.
 - 60NiTi is bearing hard (Rockwell C60) but only half as stiff as steel.
 - Buehler found 60NiTi too difficult to manufacture but modern (ceramic) processing methods enable 60NiTi bearings with remarkable properties.



Fine Grained 60NiTi microstructure via powder metallurgy



Highly polished 60NiTi bearing balls



Technical Properties Comparison:

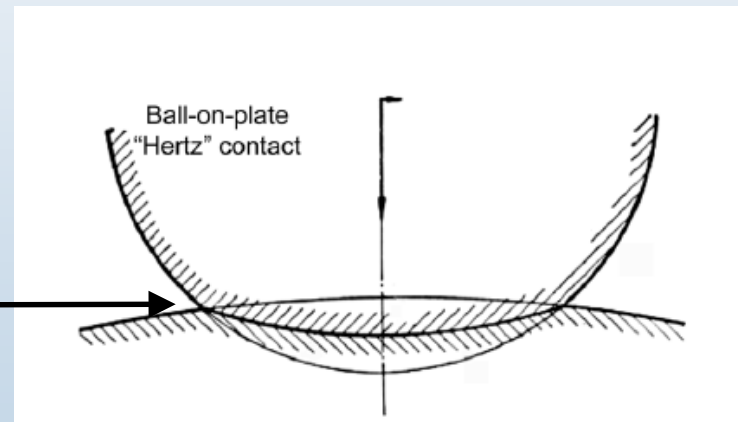
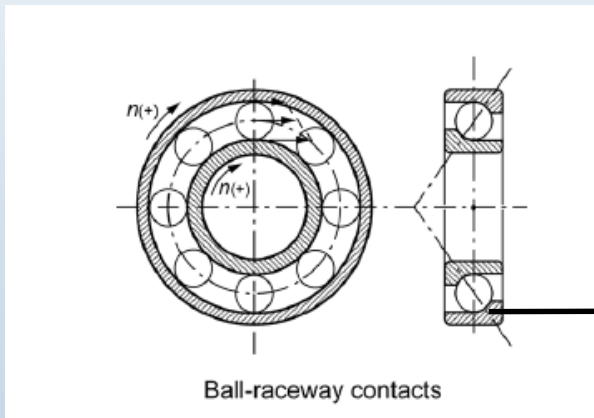
Property	60NiTi	440C	Si ₃ N ₄	M-50
Density	6.7 g/cc	7.7 g/cc	3.2 g/cc	8.0 g/cc
Hardness	56 to 62 HRC	58 to 62 HRC	1300 to 1500 Hv	60 to 65 HRC
Thermal conductivity W/m-°K	~9 to 14	24	33	~36
Thermal expansion	~11.2×10 ⁻⁶ /°C	10×10 ⁻⁶ /°C	2.6×10 ⁻⁶ /°C	~11×10 ⁻⁶ /°C
Magnetic	Non	Magnetic	Non	Magnetic
Corrosion resistance	Excellent (Aqueous and acidic)	Marginal	Excellent	Poor
Tensile/(Flexural strength)	~1000(1500) MPa	1900 MPa	(600 to 1200) MPa	2500 MPa
Young's Modulus	~95 GPa	200 GPa	310 GPa	210 GPa
Poisson's ratio	~0.34	0.3	0.27	0.30
Fracture toughness	~20 MPa/√m	22 MPa/√m	5 to 7 MPa/√m	20 to 23 MPa/√m
Maximum use temp	~400 °C	~400 °C	~1100 °C	~400 °C
Electrical resistivity	~1.04×10 ⁻⁶ Ω-m	~0.60×10 ⁻⁶ Ω-m	Insulator	~0.18×10 ⁻⁶ Ω-m

- *Modulus is ½ that of steel, yet hardness is comparable.*
- *Ultra-high static load capacity.*
- *Tensile strength akin to ceramics.*
- *NiTi alloys are brittle but do not rust.*



Contact Engineering: Ball-Race

- When hard surfaces contact
 - Forces are transmitted at small, concentrated contact points (Hertz).
 - Resulting stresses cause deformations that help “spread the load”.
 - Contact area is a function of the geometry, material stiffness and load.
 - High stiffness (modulus) inhibits deformations leading to small contact area and high stresses (contrast with a tire contacting the ground).

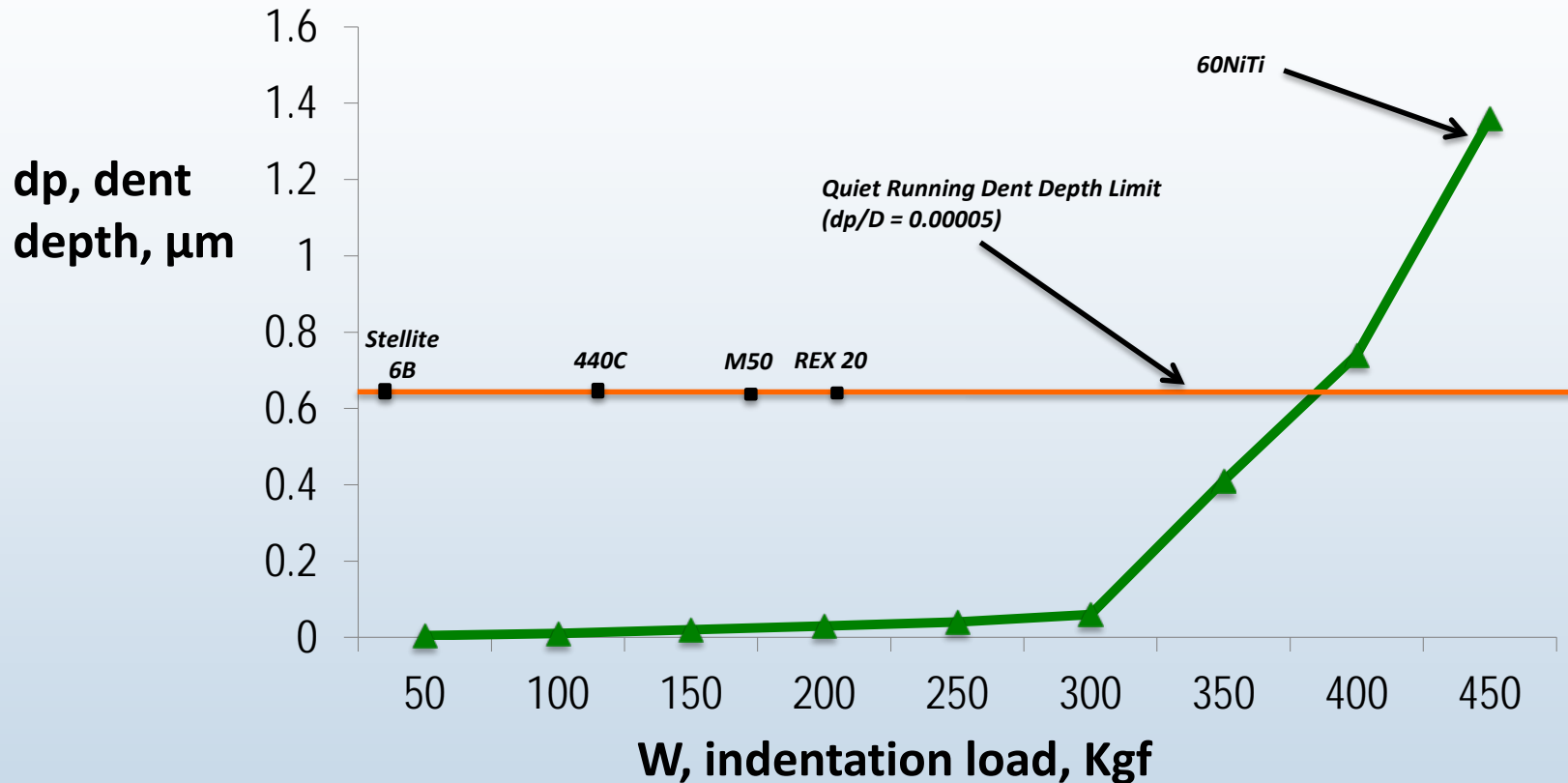


- *Hard surfaces can dent*
 - *Even modest loads can exceed stress capability limits.*
 - *Bearing raceways are particularly prone to Brinell dent damage.*



Dent Depth vs. Load

(Si_3N_4 ceramic ball pressed against 60NiTi plate)



- 60NiTi combines high hardness, reduced stiffness and superelasticity to increase load capacity over other steels dramatically.
- But what about rolling contact fatigue, RCF?



Rolling Contact Fatigue

(Accelerated Test Protocol: 3 Ball-on-Rod)

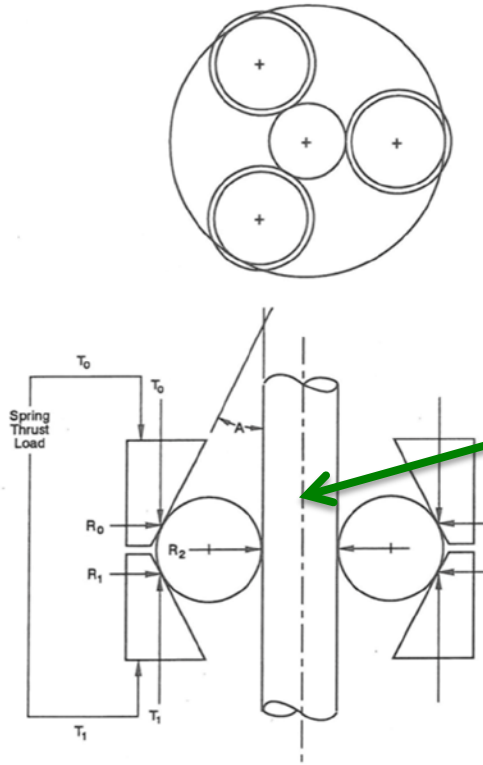


Figure 7.4-9. Rolling Contact Fatigue (RCF) Specimen Arrangement in which Steel Bearing Balls are Loaded against a Rotating NiTi Rod. Tests are run until rod damage is detected or 800 hours of operation is reached.

- 3-Ball test allows for RCF evaluation of new materials prior to investing in the manufacture of full-scale bearings



Early Rolling Contact Fatigue: Cast 60NiTi

Table V-Preliminary rolling contact fatigue (RCF) life for 60NiTi rods (loaded against M50 steel balls, 3600 rpm, mineral oil lubricant).

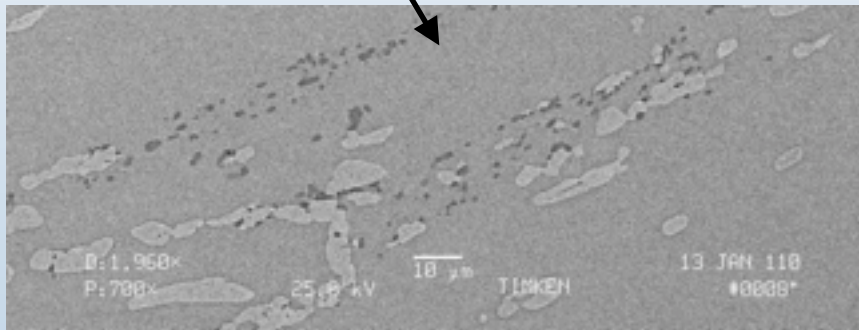
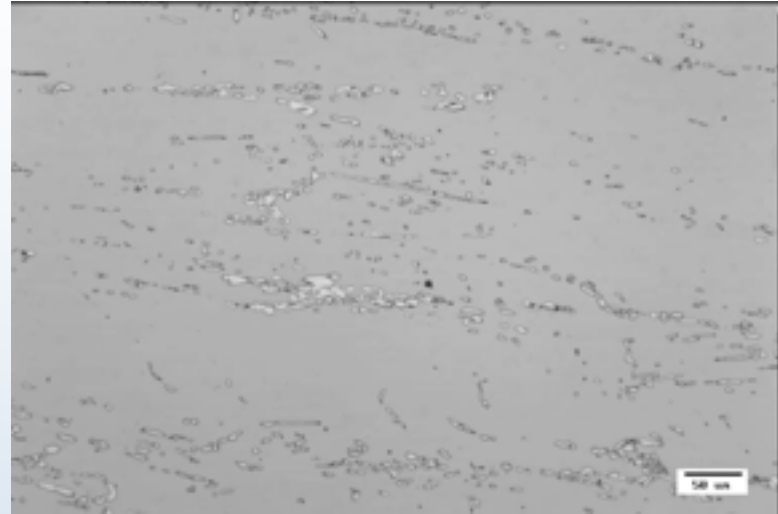
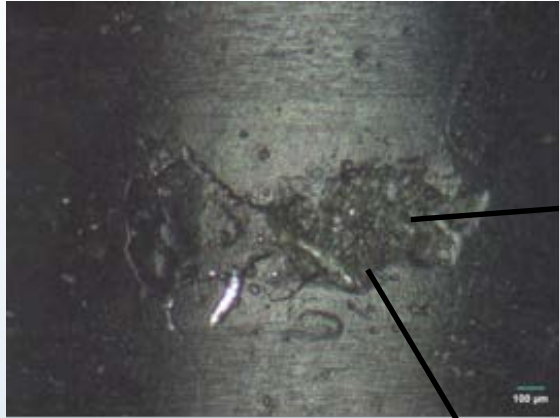
RCF Stress Level, Ksi	Wear Track Width, μm	RCF Life, hr
429	850 +/- 18	5.7 +/- 3.2
356	701 +/- 25	5.4 (typical)
266	540	13.8 to 841(no failure)

- Modern bearing steels yield long life at 500 ksi (~3.5GPa).
- Cast 60NiTi's life-threshold stress varies widely.
- Results linked to material quality.



Rolling Contact Fatigue:

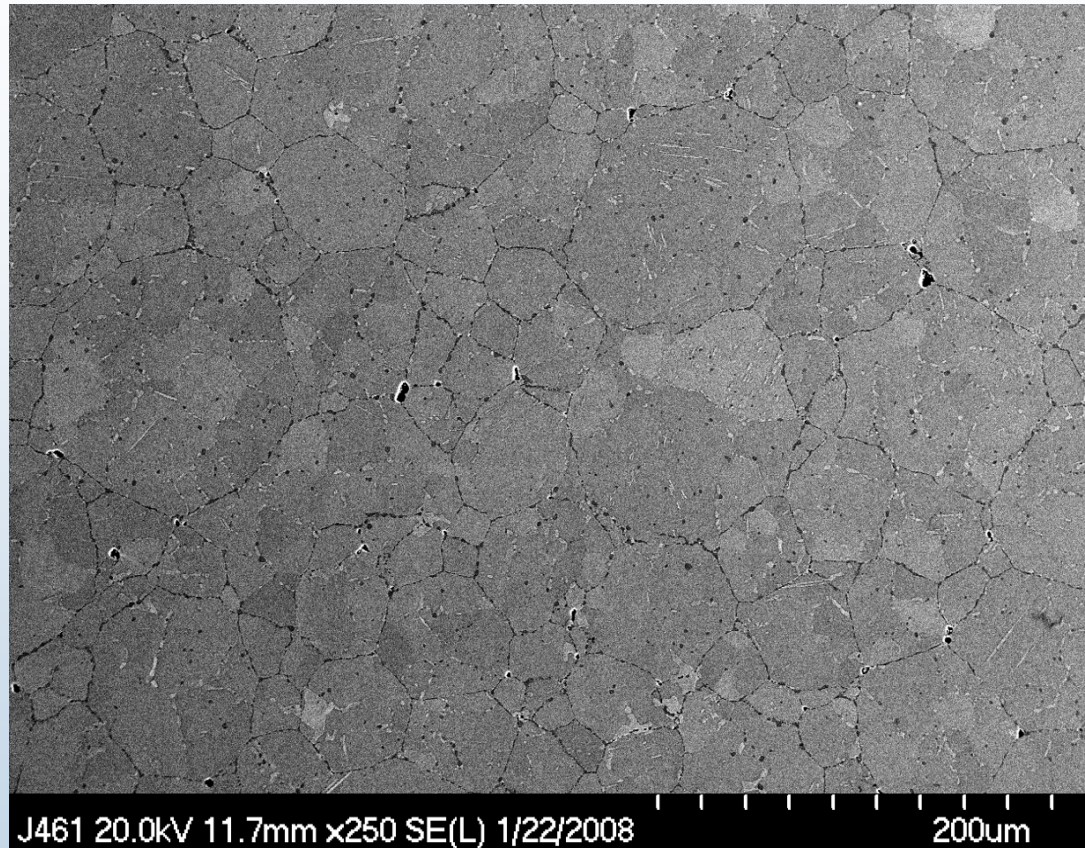
Early cast 60NiTi rod microstructure



- Internal defects such as precipitates and voids are fracture initiation sites for hard bearing materials and must be eliminated through processing and alloying.
- Newly emerging processing expected to lead to enhanced RCF life.



Rolling Contact Fatigue: PM Material?

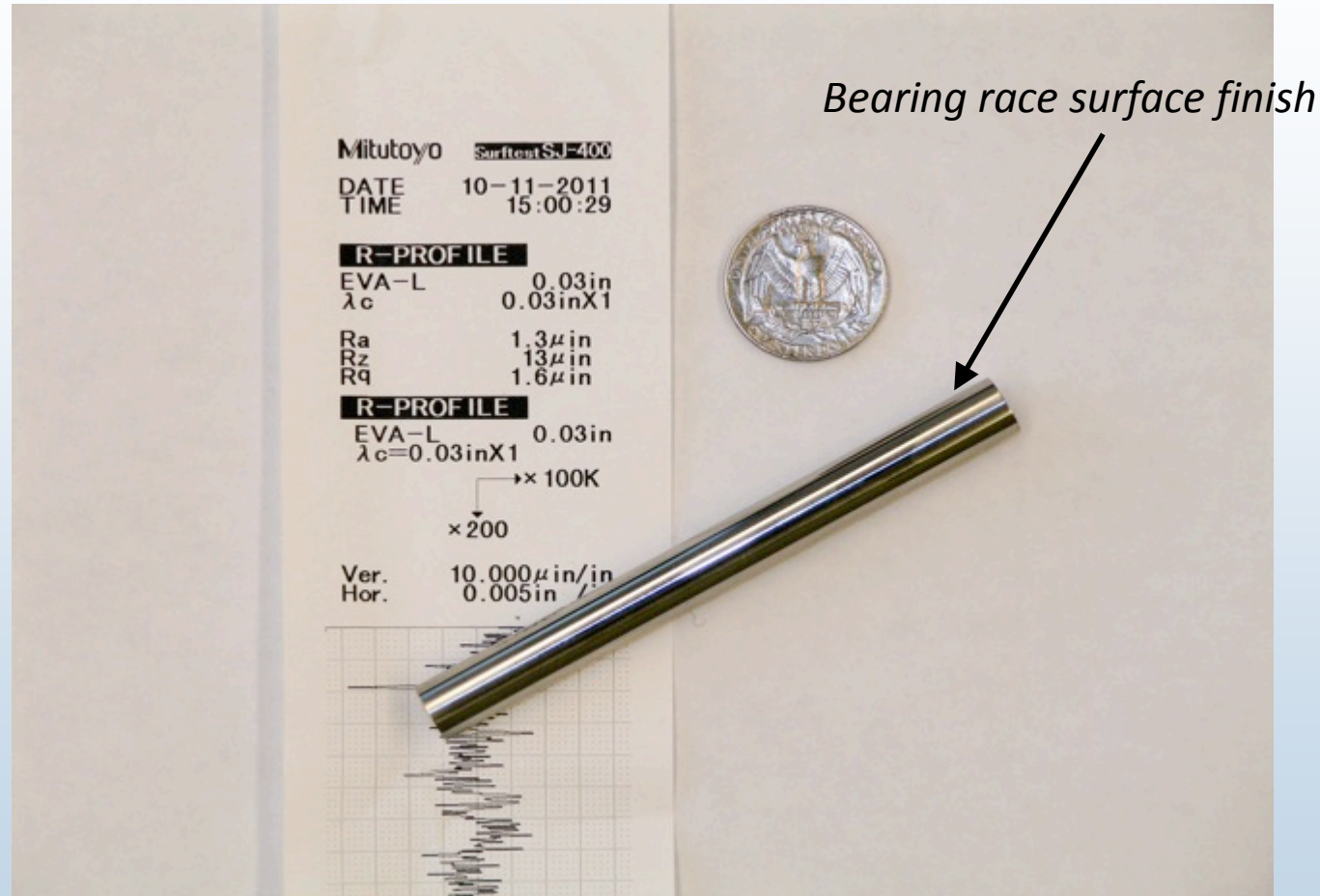


Powder Metallurgy 60NiTi has fine, uniform microstructure



Rolling Contact Fatigue

(PM Rod Specimen: represents bearing race)





Rolling Contact Fatigue

(Updated test results: more representative materials)

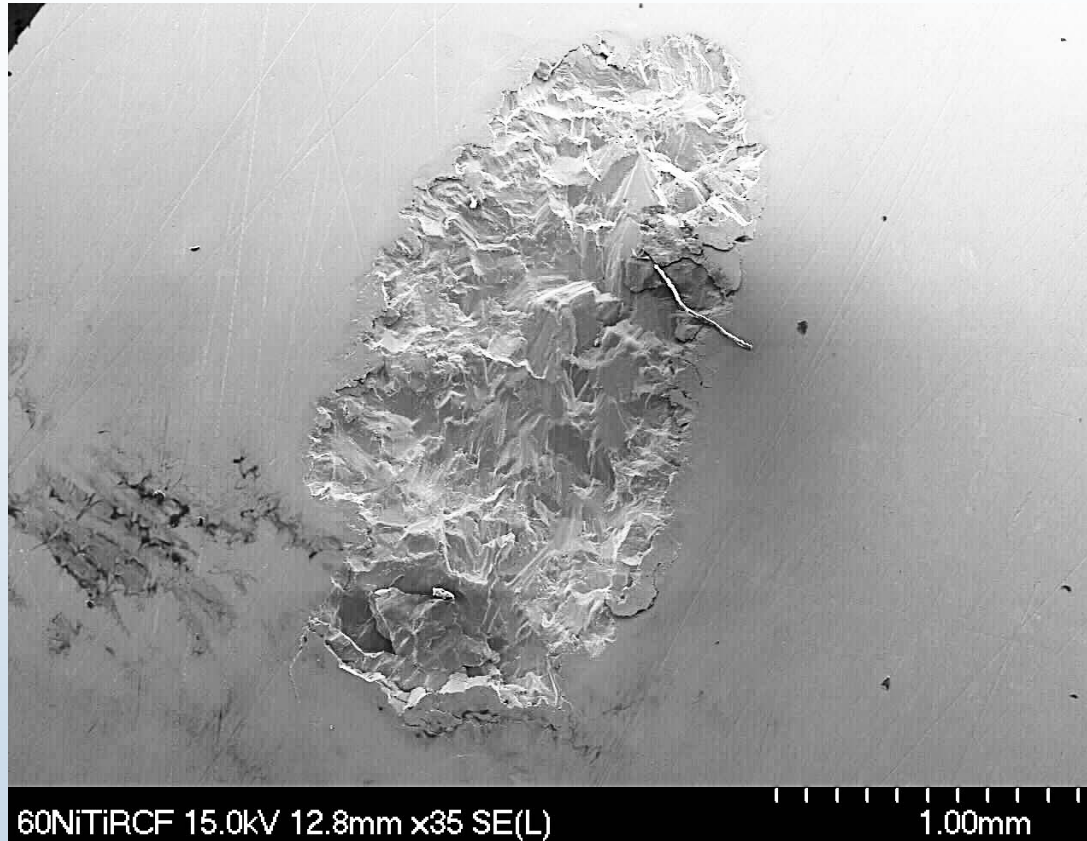
Baseline
Continuous
Stress Limit

Table X-Three Ball-on-Rod Rolling Contact Fatigue Preliminary Results (test duration to first detected surface damage) {3600 rpm, steel balls, NiTi rods, oil drip lubrication}				
Rod Specimen	Peak Contact Stress (GPa)			
	1.7 GPa	2.5 GPa	3.3 GPa	4.1 GPa
PM-60NiTi (Baseline)	>800 hr	18-847 hr	<20 hr (tests ongoing)	<0.3 hr
PM-60NiTi (With inclusions)	131-800 hr	11-800 hr	0.2 to <236 hr	-----
60NiTi (Cast & hot-rolled)	13-800 hr	<5 hr	<5 hr	-----
59NiTi + X alloy (Cast)	>800 hr	>800 hr	0.1 to 970 hr	-----
59NiTi + X Alloy (Cast and extruded)	>800 hr	400 to 800+ hr	0.1 to <31 hr	-----

- Modern bearing steels yield long life to at least 3.5GPa.
- 60NiTi begins to exhibit permanent dents at stresses above ~3.0GPa.
- 60NiTi's life limiting fatigue stress is lower (~2GPa) but is adequate for some applications. RCF results highly dependent upon material quality.



Rolling Contact Fatigue: PM 60NiTi rod

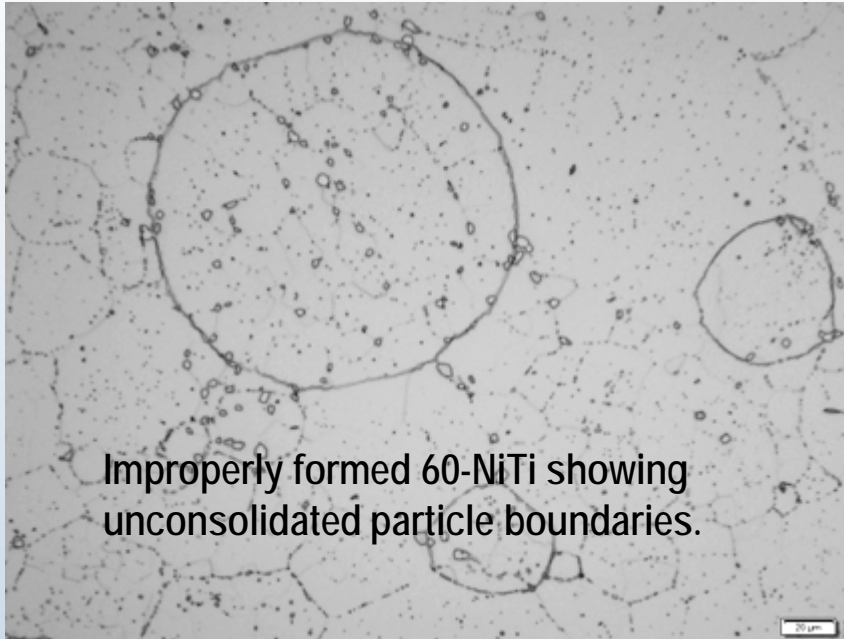


PM 60NiTi rod running surface after test.

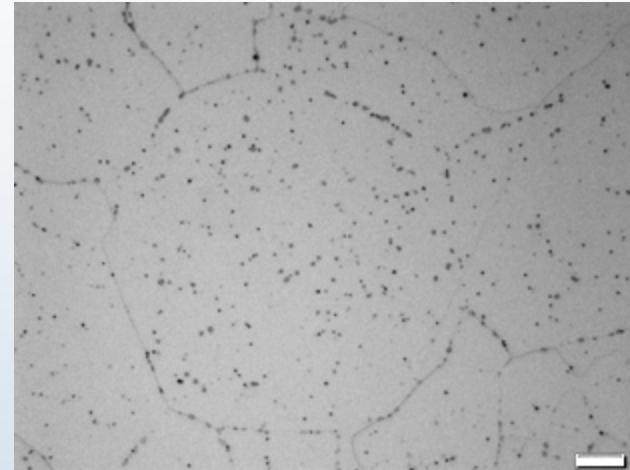


RCF Stress Limit: Linked to microstructure

Flawed PM60NiTi
1.7GPa RCF Stress Limit



Baseline PM60NiTi
~2.5GPa RCF Stress Limit



Nominal 60-NiTi showing well bonded prior particle boundary

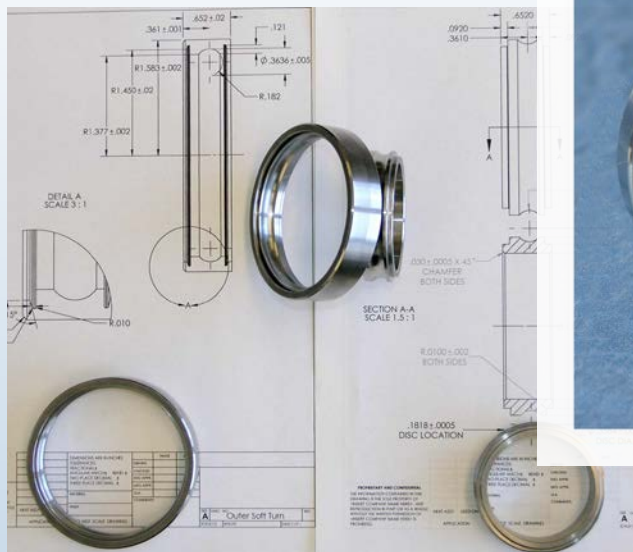
- *Microstructure affects RCF stress capability in the 3-Ball test*
- *Does the effect of quality translate to full-scale bearings?*



Centrifuge Bearings: 50mm bore 60NiTi Hybrid

Two batches of bearings fabricated

Low Quality 60NiTi
(2011)



NASA C-2012-3942



National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field

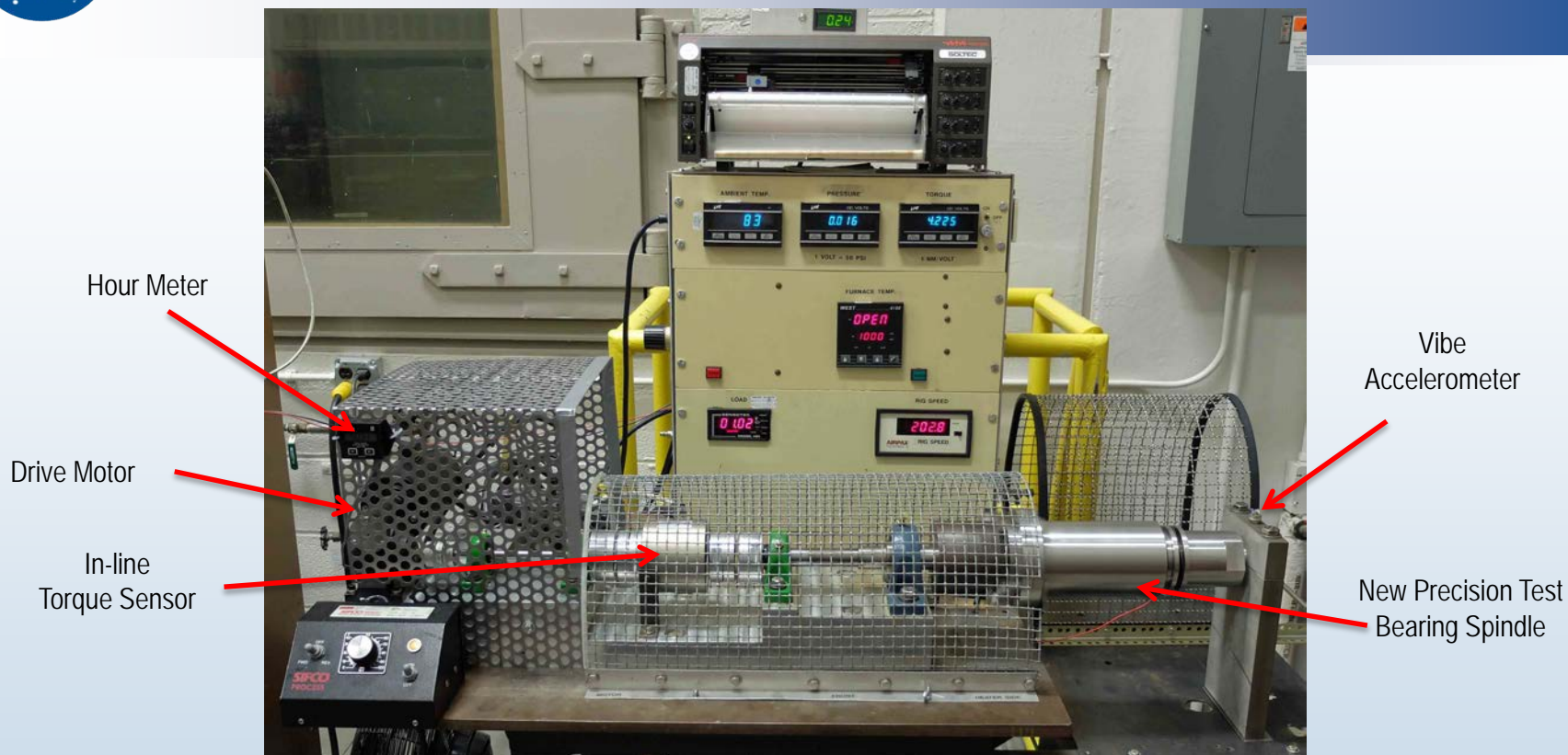
High Quality 60NiTi
(2013)



- *Quality level affected 3-ball RCF stress capability.*
- *Does the effect of quality translate to full-scale bearings?*



Life Test: 50mm Hybrid NiTi Bearing



- *Pair of 50mm hybrid (60NiTi races, Si_3N_4 balls) ball bearings, 90 pound axial preload (~1.1 GPa stress).*
- *200 rpm, continuous turning, torque measurements.*
- *Accelerometer with hourly vibe spectrum data capture used for health monitoring.*
- *Tests continued (24/7) until vibration changes or 5000 hours reached.*



Life Test #1: Low Quality 60NiTi, 1156 hours



Inner race pit

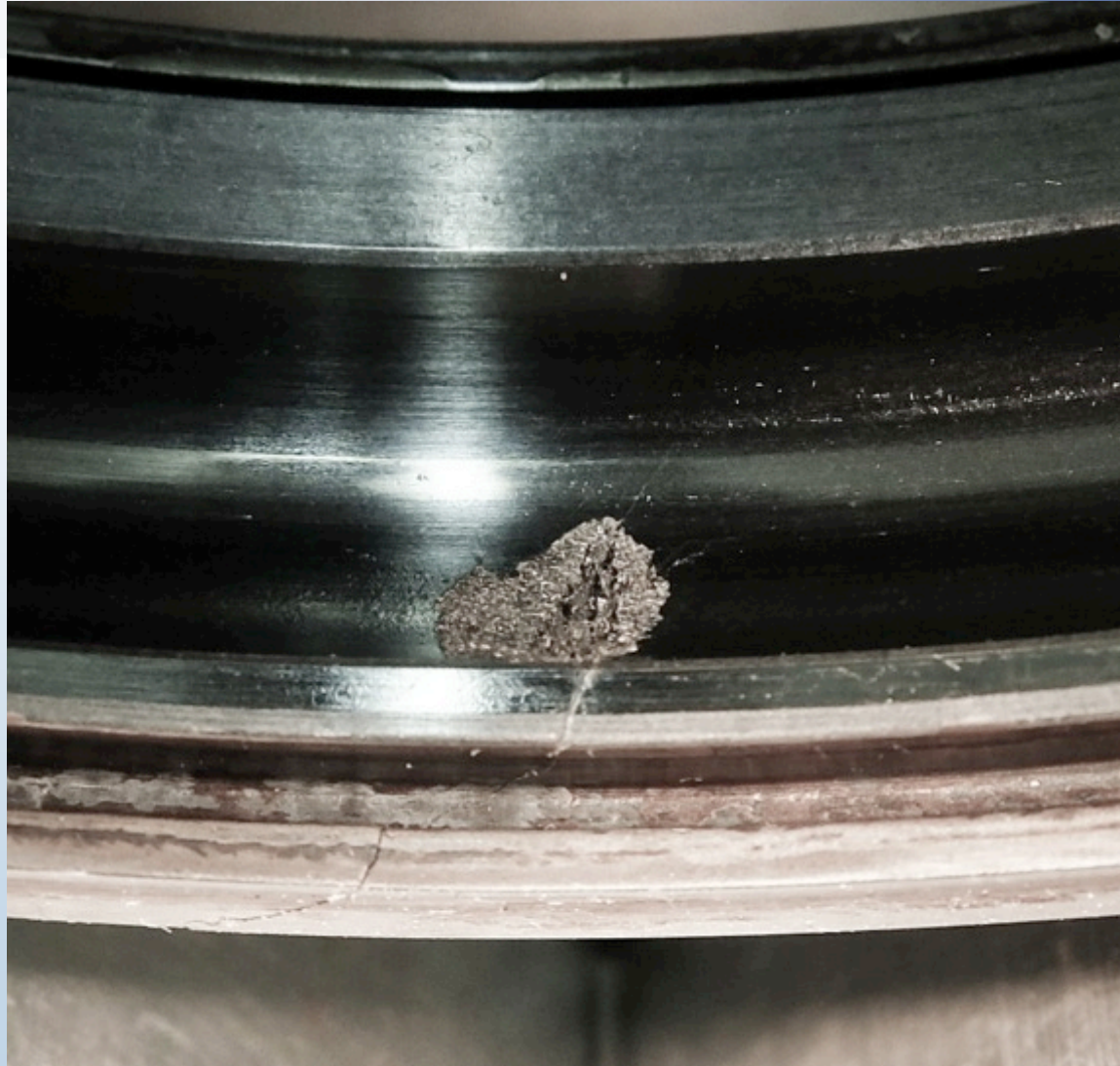


Outer race pit and cross-race crack

- *Test began normally, low torque, smooth operation.*
- *Inspection after 600 hours. Bearing surfaces and lubricant in as-new condition.*
- *At 1156 hours, rig making noise. Full inspection of bearings.*
- *Fatigue damage, debris contaminated grease.*



Life Test #1: Low Quality 60NiTi



Outer race crack propagation through entire race.

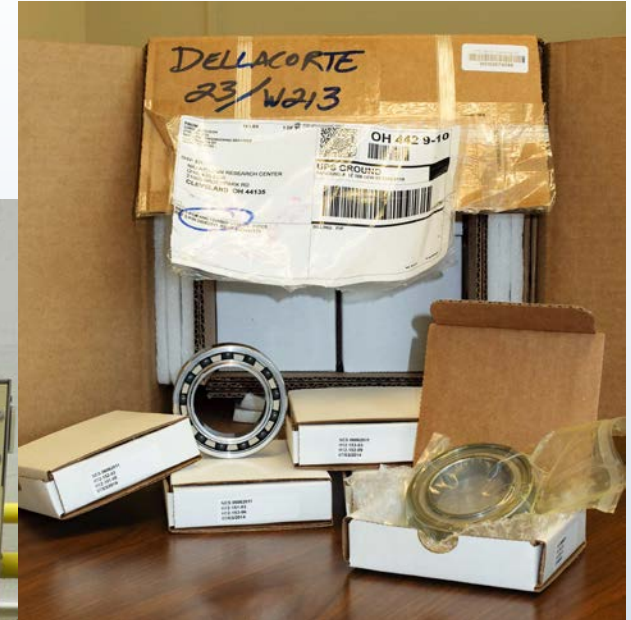
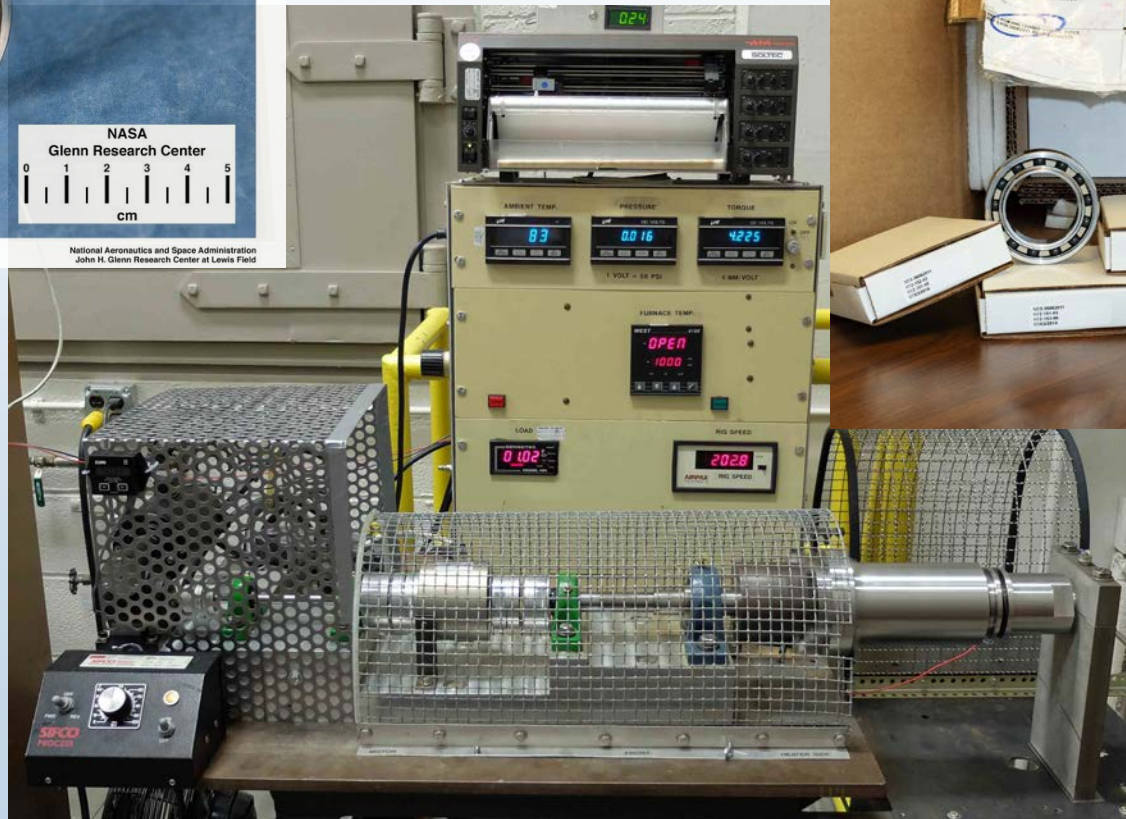


Life Test #2: High Quality 60NiTi

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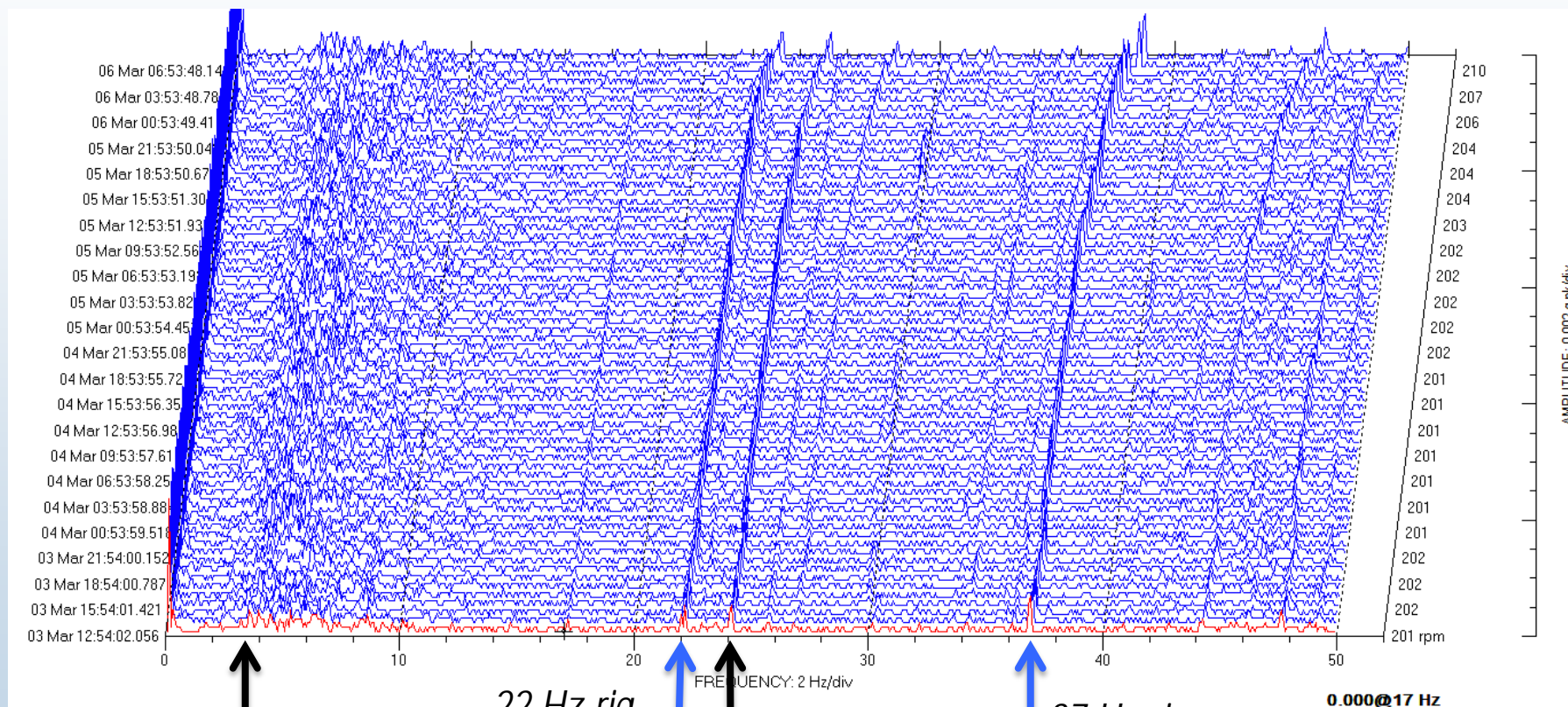
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Life Test #2: Vibration plot at 1100 hours

- Typical vibration cascade plot for three day period shown below:



3.2 Hz-shaft
rpm

22 Hz-rig
support brg

24 Hz-ball pass
frequency

37 Hz-rig
support brg



Life Test #2: High Quality 60NiTi-1100 hours



- *1100 hour inspection-all surfaces and lubricant in as-new condition*
- *Bearings re-greased and returned to test.*



Life Test #2: Inspection at 5000 hours

- *Lubricant grease looks new, no visible wear or damage on races.*





Bearing Life Test: Inspection at 5000 hours

- *Inner race surfaces shiny and without any apparent wear or other signs of contact damage.*





Bearing Life Test: Inspection at 5000 hours

- *Outer race looks fine too.*



- *Bearings were cleaned, visually inspected, re-greased and re-started.*
- *Health monitoring (torque and vibration) used to indicate failure.*
- *Tests to be halted at 10,000 hours.*



Summary Remarks

- Sub-component RCF tests indicate relation between material quality and stress capability.
- Full-scale bearing life tests corroborate the sub-component tests.
- High quality 60NiTi, largely free from inclusions and other flaws can provide long running life under modest continuous stress levels.
- NiTi bearing materials offer several unique attributes (high static load capability and corrosion resistance) that make them attractive candidates for space mechanisms.
- As the technology matures, the growing knowledge-base coupled with alloy improvements will enable expanded use of these new materials allowing designers to take advantage of NiTi's unique capabilities.



Thank You!



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